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# Thermal/Structural Tailoring of Engine Blades (T/STAEBL)

## Theoretical Manual

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## **1. STAEBL PROGRAM DESCRIPTION**

The Thermal/Structural Tailoring of Engine Blades (T/STAEBL) computer program was developed to perform engine hollow, cooled turbine blade and vane numerical optimizations. These airfoil optimizations seek a minimum weight or cost design that satisfies realistic blade design constraints, by tuning from one to a hundred design variables.

The T/STAEBL analyses include a boundary layer analysis, an internal cooling network analysis, a conduction heat transfer analysis, a creep life analysis, and a finite element stress and vibrations analysis. Available design variables, all of which may be functions of radial span, include cavity wall thicknesses; rib thicknesses; trip strip height, pitch, and angle; pedestal diameter and spacing, and film hole diameter and spacing. Available constraints include natural frequencies, stress, flow rate, aerodynamic loss, metal temperatures, and foil life. For the objective function of the cooled blade optimization, an arbitrary linear combination of blade (or vane) weight, stress, flow rate, aerodynamic loss, metal temperatures and foil life is available.

To perform cooled airfoil optimizations, T/STAEBL utilizes three classes of analysis: an optimization algorithm, a geometry update algorithm, and cooled airfoil analysis modules. The analysis modules are executed by a shell control program. The modules communicate with the user and with other modules through a file data base structure.

To use the T/STAEBL cooled airfoil optimization system, geometry, flow, and thermal descriptions are required. These inputs are detailed in the T/STAEBL User's Manual (Reference 1).

The T/STAEBL system has been applied to a turbine blade of the Energy Efficient Engine, which was designed under NASA Contract NAS3-20646.

### **1.1 T/STAEBL Data Block Structure**

The T/STAEBL system, due to its size and complexity, is organized very differently than the Aero/STAEBL system (Reference 2). In the Aero/STAEBL program, by employing overlays and a common scratch storage area, the entire system was able to run as a single computer program. The T/STAEBL system, and its associated modules, are much too large to permit a similar mode of operation, however.

The T/STAEBL system is organized as a collection of totally independent, stand-alone modules. All module to module communications are done through a data base system. Due to the size and variety of data forms and disciplines to be communicated, a single data base "neutral" file would be extremely complicated. Instead, a series of independent data files, called Blocks, are maintained. The Blocks are identified by numbers, such as 0012.

The data blocks may contain basic input data, data produced by one program that will be required by another, or system outputs. To aid system development, increase flexibility, and speed new user learning, all data blocks are stored in ASCII format. Thus, any intermediate inputs and outputs may be edited and interpreted by the user. A detailed list of the data blocks, their number designations, and their usage, is provided in Table I.

Blocks are stored as data files in the user's directory and are named according to the following format: b0iii.j, where iii is the data block number, and j is the airfoil cross-section number. For files where section is not relevant, such as Block 0, Control Information, the j index is a 0. The file for Block 0 is thus named: "b0000.0".

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**Table I. T/STAEBL System Data Blocks**

---

<u>Block Number</u>	<u>Airfoil Sections</u>	<u>Description</u>
0000	0	Control Information
0001	1-5	Section Geometry
0012	0	Materials Data
0016	0	Cycle Definition
0017	1-5	Row and Column Breakup
0022	1-5	Creep
0023	1-5	Film Hole Geometry
0024	1-5	HGAS Film
0025	1-5	TGAS Film
0026	1-5	ETA Film
0027	1-5	HCOOLANT
0028	1-5	TCOOLANT
0029	1-5	HPEDESTAL
0030	1-5	TPEDESTAL
0031	1-5	HFILMHOLE
0032	1-5	TFILMHOLE
0037	1-5	Pedestal Geometry
0038	1-5	Flag Points
0093	1-5	External PS/PT
0095	0	External P-Total
0096	0	Internal P-Total
0097	0	External T-Total
0099	0	1DHT Reference Data
0101	1-5	Pressure Side Boundary Layer Data
0102	1-5	Suction Side Boundary Layer Data
0104	1-5	Film Effectiveness
0400	1-5	Heat Transfer, Internal Cooling Base Input
0401	0	Internal Cooling Input Files
0500		Optimizer Inputs and Outputs
0501	0	Coating Thickness
0502	0	Finite Element Mesh Control
0503	0	Optimization Control
0504	0	Network Analysis Post-Processing
0505	0	Network Analysis Iteration Control
0506	0	Network Analysis Post-Processing
0507	0	1-D Heat Transfer Control
0509	0	Finite Element Meshing Parameters
0510	0	Design Variable Increments
0511	0	Base Values of Design Variables
0512	1-5	Thermal Analysis Flag Points
0513	0	Global Section Radii
0514	0	Network Cross Reference Table
0515	0	Analysis Results File
0516	0	Finite Element Analysis Control
0517	0	Number of Uncooled Elements

---

## 1.2 T/STAEBL System Organization

The T/STAEBL data base structure allows for a very general and flexible organization of the associated analyses. To do a proper optimization of a cooled airfoil, however, a very detailed and carefully interlocked analysis sequence must be performed.

The overall module flow for T/STAEBL is shown in Figure 1. The first module to be called, after some basic data inputs, is the INIT module. This module, referencing the optimization inputs, sets up the appropriate data for the ADS optimizer (Reference 7). Two calls to the optimizer are required – one to initialize its parameters, and another to initialize the restart loop. This process deviates from the usual execution mode for ADS, but is required to enable T/STAEBL to run in the optimizer's "restart" mode. From this point on, T/STAEBL departs from the usual ADS optimization procedure, because other modules will be separately executed, as in a batch mode.

A part of the T/STAEBL optimization capability is the option for design variable scaling. At this point, however, scaling is not yet possible – a typical analysis might have a design variation of zero from the base blade, and the actual parameter value (e.g., wall thickness) is as yet unknown, for it is strictly a function of the as-yet unanalyzed coordinate data block inputs.

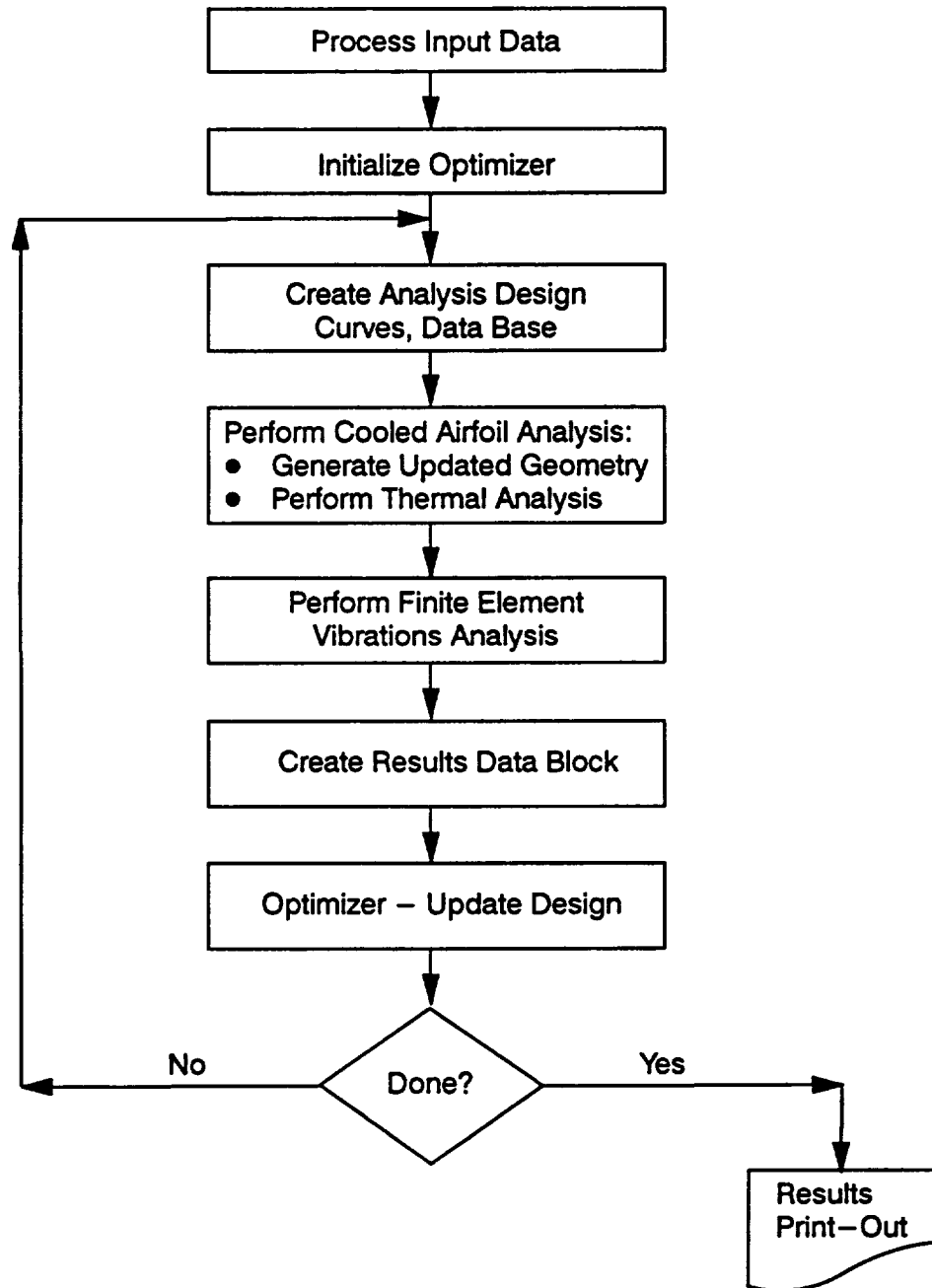
To enable later design scaling, the TAILOR module is now executed for the initial geometry. This module will prove very important to the T/STAEBL system, for it interfaces between the design variable choices of the optimizer, and the initial airfoil coordinate inputs ("base blade"), to produce geometry files for the updated airfoil, called the "current blade". TAILOR also produces Block 511, Base Values of Design Variables. This block contains the information required for design scaling, such as initial wall thickness, rib thickness, etc.

At this point, the analysis is ready to enter the optimization loop. The optimizer is called to select a candidate set of design variables. On the very first call, the original design (base plus any initial design changes) will be analyzed.

We are now ready to execute the TAILOR module to update the design files. A note on bookkeeping of design variables is in order: while ADS works with only those variables that are actually changing in a run (compressed variable list), and does not have to associate this list with any physical quantities, TAILOR must have full authority (full variable list) to update any potential design variable, and must be capable of associating physical changes to any design parameter change. To accomplish the variable list expansion and contraction, T/STAEBL uses the XPANDO module. XPANDO compares the current design variables with all potential design variables, and expands the compressed variable list to a full size list. Parameters that are constant for a given run will stay zero in the full size design parameter change list.

TAILOR takes the full variable change list, and uses it to create an updated design file set, for the current blade. This current blade will now be passed through the entire T/STAEBL analysis set, including the cooled airfoil analyses of Section 1.2.2, and the finite element analyses discussed in Section 1.2.3.

The first step in the analysis process is the cooled airfoil analysis, detailed in Section 1.2.2. In this super-module, the airfoil is analyzed for performance, life, and cooling requirements. Pertinent performance data are stored in Block 515.



**Figure 1** *T/STAEBL Overall Program Flow*

Subsequent to the thermal analysis modules, a finite element vibratory analysis is conducted. Using the current geometry, a shell finite element model of the cooled airfoil is constructed. This mesh, with a beam model of the neck section, is passed through the finite element module, to determine the natural frequencies.

After the finite element analysis has been performed, all analysis data is available. The CONPROC module reviews the results of the finite element analysis, as well as File 515, to assemble a list of constraint and objective data for the selected airfoil design. This information is passed to the optimizer, which selects a new design, and the loop is started again, unless an optimum design has been found.

### **1.2.1 Shell Driver**

Control of the T/STAEBL program lies with a shell program. The shell program monitors system progress, maintains the data file structures, calls the appropriate analysis modules, and terminates the analysis when appropriate. For execution on the NASA–LeRC CRAY, the shell was created in UNICOS format.

### **1.2.2 Cooled Airfoil Analysis System**

The key to the T/STAEBL optimization system is its link to a high quality cooled airfoil analysis system. As detailed in Section 2.3, the T/STAEBL cooled airfoil analysis is quite complete, including modules to:

1. Update the base cooled blade design
2. Perform necessary analysis breakups
3. Add coating elements
4. Apply boundary layer conditions
5. Determine internal flow film coefficients
6. Perform a network heat transfer analysis
7. Reach a converged thermal solution
8. Perform a stress and creep life analysis for three–pass, cooled, hollow turbine blades and vanes.

### **1.2.3 Finite Element Analysis Modules**

To perform a finite element vibrations analysis of a cooled airfoil, an efficient yet accurate model of the geometry is required. To remain feasible for a computer time usage in STAEBL's optimization application, a plate element, rather than a brick element, model was selected. To accurately model the geometry, each wall is modelled as a separate array of plates. Ribs, which tie the walls together, are also modelled using plate elements. The same procedure was applied to the trailing edge, where pedestals provide a wall to wall shear tie. Details of the finite element model generator are included in Section 2.5.1.

To accurately model the airfoil vibratory characteristics, the neck flexibility must also be included. These sections, while included in the analysis, do not currently include any design variables. Thus, these inputs, which are supplied by the user in Block 503, are not allowed to vary. In T/STAEBL, the airfoil neck is modelled using beam elements that are tied to the root of the airfoil using rigid elements, which automatically write the correct kinematic links between the neck and the airfoil, even though the airfoil grid locations may be varying from design step to design step. The beam elements are oriented so that their minimum bending inertia aligns with the disk broach angle.

### 1.2.3.1 The T/STAEBL Finite Element Analysis

The airfoil natural frequencies are calculated in T/STAEBL by using an in-core, limited size finite element analysis. The finite element code is fashioned after NASTRAN, so that a mesh run in T/STAEBL or in NASTRAN will give nearly identical results. While several elements are available, the elements employed by T/STAEBL include a spring element, a beam element, and a four noded quadrilateral thin shell element.

Specifically designed for rotating airfoils, the finite element module first performs a static analysis, then calculates a differential stiffness matrix. Third, the finite element analysis calculates the natural frequencies of the rotating blade. In the static case (vane), the first two steps are skipped.

### 1.2.3.2 The STAEBL Plate Finite Element

Similarity with the NASTRAN finite element program has been preserved in T/STAEBL by employing a thin shell element very similar to the NASTRAN QUAD4 (Reference 3). Features of the solution procedure include:

1. Recognition of thickness taper
2. Properly stacked plate element meshes model airfoil pretwist and camber
3. Laminated composite analysis capability
4. Element differential stiffness
5. Lumped mass approximation generates a storage efficient diagonal mass matrix.

### 1.2.3.3 Guyan Reduction

The Guyan reduction procedure (Reference 4) has proven to be a very successful means of reducing the number of degrees of freedom used in dynamic analysis, while minimizing loss of accuracy in the lower frequency modes. The procedure is based on the fact that many fewer grid points are needed to describe the inertia of a structure than are required to describe its stiffness with comparable accuracy. The reduction procedure thus allows a condensation, resulting in a much smaller equation set for dynamic analysis.

The reduced, or omitted, degrees of freedom,  $U_o$ , and the remaining, or analysis degrees of freedom,  $U_a$ , relate to static loads according to:

$$\begin{bmatrix} K_{aa} & K_{ao} \\ K_{oa} & K_{oo} \end{bmatrix} \begin{Bmatrix} U_a \\ U_o \end{Bmatrix} = \begin{Bmatrix} F_a \\ F_o \end{Bmatrix} \quad (1)$$

Neglecting the forces  $F_o$ , we find;

$$\{U_o\} = [Goa] \{U_a\} \quad (2)$$

where

$$[Goa] = -[K_{oo}]^{-1} [K_{oa}] \quad (3)$$

The matrix decomposition required to calculate  $[Goa]$  in Equation (3) was accomplished by using the LEQ1PB subroutine of the International Mathematics and Statistics Library (IMSL).

The reduced stiffness matrix thus becomes:

$$[Kaa] = [K\bar{a}\bar{a}] + [Kao] [Goa] \quad (4)$$

The reduced mass matrix, determined by equating the kinetic energies before and after the reduction, is:

$$[Maa] = [M\bar{a}\bar{a}] + [Mao] [Goa] + [Goa]^T ([Moa] + [Moo] [Goa]) \quad (5)$$

#### 1.2.3.4 Differential Stiffness

The determination of natural frequencies for rotating blades requires the inclusion of differential stiffness effects due to centrifugally induced steady stresses. In order to allow for differential stiffness generation, static deflections are determined for the case of centrifugal loadings, using the LEQT1P solver of the IMSL package. The static displacements are then used to create the element differential stiffness matrix, KDGG. The energy of differential stiffness,  $U_d$ , consists in part of energy of bending motions,  $U_{db}$ , and in part of membrane (in-plane) motions,  $U_{dm}$ :

$$U_d = U_{db} + U_{dm} \quad (6)$$

As shown in Reference 5, the bending and membrane energies are related to the membrane stresses and the bending rotations, giving:

$$U_d = \frac{hA}{2} \{ \bar{\sigma}_x \omega_y^2 + \bar{\sigma}_y \omega_x^2 - 2\bar{\tau}_{xy} \omega_x \omega_y + \bar{\sigma}_x (\omega_z^2 + 2\omega_z \varepsilon_{xy}) + \bar{\sigma}_y (\omega_z^2 - 2\omega_z \varepsilon_{xy}) + 2\bar{\tau}_{xy} (\varepsilon_y - \varepsilon_x) \omega_z \} \quad (7)$$

where  $hA$  is the element volume,  $\bar{\sigma}_x$ ,  $\bar{\sigma}_y$ , and  $\bar{\tau}_{xy}$  are the element membrane stresses, and  $\omega_x$ ,  $\omega_y$ , and  $\omega_z$  are the rotations in the element coordinate system, shown on Figure 2.

The centrifugal mass matrix, which accounts for the change in direction of centrifugal loads with displacement, gives the nodal incremental load in global coordinates ( $x$  = radial,  $z$  = axial), as:

$$\begin{Bmatrix} \Delta F_x \\ \Delta F_y \\ \Delta F_z \end{Bmatrix} = - \begin{bmatrix} M\Omega^2 & 0 & 0 \\ 0 & M\Omega^2 & 0 \\ 0 & 0 & 0 \end{bmatrix} \begin{Bmatrix} \Delta X \\ \Delta Y \\ \Delta Z \end{Bmatrix} \quad (8)$$

This "stiffness," transformed into local nodal coordinates, is combined with the differential stiffness matrix and the original blade stiffness, to give the blade's total at-speed stiffness. The total blade stiffness matrix, after reduction to analysis-set size, is solved to find the at-speed blade natural frequencies.

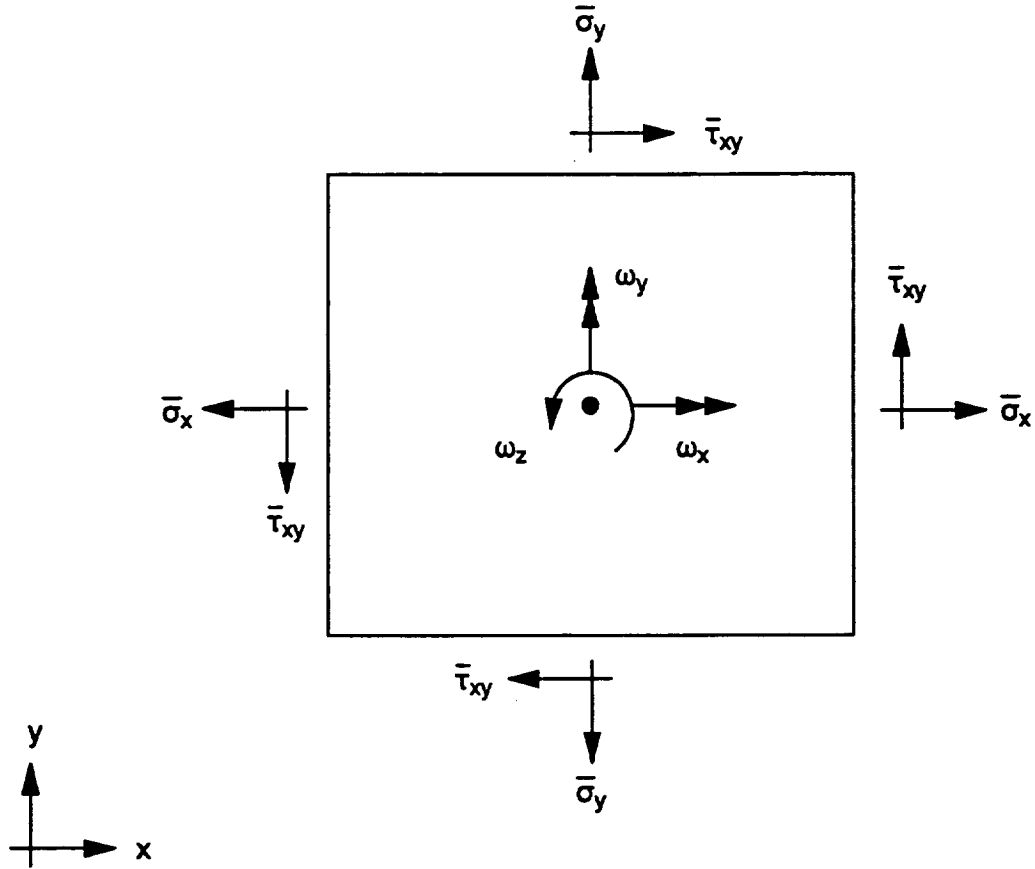


Figure 2 Stresses and Rotations of Prestress Stiffened Plate Element

#### 1.2.3.5 Eigenvalue Solution

Once the stiffness and mass matrices have been reduced, they are, in general, symmetric but full. Due to the reduction procedure, however, they are relatively small in size. The unsymmetric eigenvalue problem is formed:

$$-\omega^2 \{Ua\} + [Maa]^{-1} [Kaa] \{Ua\} = \{0\} \quad (9)$$

The IMSL subroutine package is again employed, using the QR method to solve the unsymmetric eigenvalue problem. Both eigenvalues and eigenvectors are extracted for the reduced size problem. IMSL routines required to perform the eigenvalue extraction include: EBALF, EHESF, EHBCKF, EQRH3F, AND EBBCKF.

#### 1.2.3.6 In-Plane Rotation Singularity Constraint

When performing plate finite element analysis, the in-plane rotations must be suppressed in relatively flat sections to prevent system ill-conditioning. On airfoils, camber is usually sufficient near the blade root to prevent in-plane rotation singularities. Near the blade tip, however, camber is low and suppressions are usually required. In large deflection analyses, the problem is further compounded by the possibility that the blade section may uncamber during the deflection process.

To prevent against possible numerical problems during the STAEBL analyses, an algorithm to provide an artificial stiffness to in-plane rotation singularities has been included in the STAEBL finite element code. The algorithm, taken from Reference 6, creates a fictitious set of rotation stiffness coefficients that is used in all elements, whether co-planar or not. For the quadrilateral plate element, the stiffness is defined by a matrix such that in element local coordinates equilibrium is not disturbed, namely:

$$\begin{Bmatrix} Mz1 \\ Mz2 \\ Mz3 \\ Mz4 \end{Bmatrix} = \alpha \, ETA \begin{bmatrix} 1. & -.333 & -.333 & -.333 \\ -.333 & 1. & -.333 & -.333 \\ -.333 & -.333 & 1. & -.333 \\ -.333 & -.333 & -.333 & 1. \end{bmatrix} \begin{Bmatrix} z1 \\ z2 \\ z3 \\ z4 \end{Bmatrix} \quad (11)$$

where the coefficient  $\alpha$  was found through numerical tests to provide numerical stability with negligible artificial system constraint for a value of  $\alpha = 1 \times 10^{-6}$ .

### 1.2.3.7 Postprocessing of Finite Element Output

The STAEBL finite element code provides, as output, static displacements and stresses (for the composite equivalent elements), as well as at-speed eigenvalues, eigenvectors, and modal equivalent stresses. These data are sent to an output file that looks much like a standard NASTRAN printout. For processing within the T/STAEBL system, the finite element printout is interpreted in the CONPROC module, which creates the ADSARG data block, which is in turn passed to the ADS optimizer for its decision purposes.

## **2. APPROXIMATE ANALYSIS AND OPTIMIZATION MODULES**

The T/STAEBL program has been developed to have a general cooled airfoil optimization capability. In its present implementation, the system is not able to alter the exterior configuration of an airfoil, however, due to the limited aerodynamic capability of the present analyses. T/STAEBL does have very general control over the interior configuration of a cooled airfoil, however. Such items as wall thickness may be varied from cavity to cavity, and also may vary as functions of the radius. Additionally, the optimization system may control any of the items listed in Table II. Note that some of the design parameters (e.g., supply pressure) are single valued, while others (e.g., wall thickness) follow design curves, allowing these parameters to vary with radius.

### **2.1 Optimizer**

To provide for a powerful and general optimization capability, the ADS optimization package (Reference 7) has been included in the T/STAEBL package. ADS is a general purpose numerical optimization program containing a wide variety of optimization algorithms. The solution of the optimization problem has been divided into three basic levels by ADS: (1) strategy, (2) optimizer, and (3) one-dimensional search. By allowing the user to select his/her own strategy, optimizer, and one-dimensional search procedure, considerable flexibility is provided for finding an optimization algorithm which works well for the specific design problem being solved.

Within T/STAEBL, the optimization algorithm is selected through the OPTIMIZE data card of Block 503, which allows for input of the ISTRAT, IOPT, ISERCH, and IOUT parameters. These parameters are used to select the strategy, optimizer, one-dimensional search, and output algorithms as described below.

For the T/STAEBL application, 057 and 047 have proven to be reliable optimization algorithm selections, and 3552 is recommended for optimizer output selection.

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**Table II. T/STAEBL Design Variables**

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<u>Variable</u>	<u>Single Valued Parameters</u>	<u>Abbreviation</u>
Supply Pressure		SUPPRS
Axial Tilt		AXTILT
Tangential Tilt		TANTILT
Secondary Material Angle		SMATANG
Coating Thickness		COATTHK

<u>Variable</u>	<u>Design Curves</u>	<u>Abbreviation</u>
Rib 1 Thickness		RIB1THK
Rib 2 Thickness		RIB2THK
Rib 3 Thickness		RIB3THK
Cavity 1 Pressure Side Thickness		CV1PTHK
Cavity 1 Suction Side Thickness		CV1STHK
Cavity 2 Pressure Side Thickness		CV2PTHK
Cavity 2 Suction Side Thickness		CV2STHK
Cavity 3 Pressure Side Thickness		CV3PTHK
Cavity 3 Suction Side Thickness		CV3STHK
Cavity 4 Pressure Side Thickness		CV4PTHK
Cavity 4 Suction Side Thickness		CV4STHK
Cavity 1 Trip Strip Height		CAV1TSH
Cavity 1 Trip Strip Pitch		CAV1TSP
Cavity 1 Trip Strip Angle		CAV1TSA
Cavity 2 Trip Strip Height		CAV2TSH
Cavity 2 Trip Strip Pitch		CAV2TSP
Cavity 2 Trip Strip Angle		CAV2TSA
Cavity 3 Trip Strip Height		CAV3TSH
Cavity 3 Trip Strip Pitch		CAV3TSP
Cavity 3 Trip Strip Angle		CAV3TSA
Pedestal 1 Diameter		PED1DIA
Pedestal 2 Diameter		PED2DIA
Pedestal 3 Diameter		PED3DIA
Pedestal 4 Diameter		PED4DIA
Pedestal 5 Diameter		PED5DIA
Pedestal 6 Diameter		PED6DIA
Pedestal 7 Diameter		PED7DIA
Pedestal Spacing		PEDSPAC
Film Hole 1 Diameter		FLM1DIA
Film Hole 2 Diameter		FLM2DIA
Film Hole 3 Diameter		FLM3DIA
Film Hole 1 Spacing		FLM1SPC
Film Hole 2 Spacing		FLM2SPC
Film Hole 3 Spacing		FLM3SPC

---

### *Strategy*

The optimization strategies available in T/STAEBL are listed in Table III. The parameter ISTRAT is sent to the ADS program to identify the strategy selected by the user. Selecting the ISTRAT=0 option transfers control directly to the optimizer. This is selected when choosing the Method of Feasible Directions or the Modified Method of Feasible Directions for solving the constrained optimization problem.

*Table III. Strategy Options*

<u>ISTRAT</u>	<u>Strategy to be Used</u>
0	<i>None. Go directly to the optimizer.</i>
1	<i>Sequential unconstrained minimization using the exterior penalty function method.</i>
2	<i>Sequential unconstrained minimization using the linear extended interior penalty function method.</i>
3	<i>Sequential unconstrained minimization using the quadratic extended interior penalty function method.</i>
4	<i>Sequential unconstrained minimization using the cubic extended interior penalty function method.</i>
5	<i>Augmented Lagrange multiplier method.</i>
6	<i>Sequential linear programming.</i>
7	<i>Method of centers.</i>
8	<i>Sequential quadratic programming.</i>
9	<i>Sequential convex programming.</i>

### *Optimizer*

The IOPT parameter selects the optimizer to be used by ADS. Table IV lists the optimizers available within T/STAEBL. Note that not all optimizers are available for all strategies. Allowable combinations are shown on Table VI.

*Table IV. Optimizer Options*

<u>IOPT</u>	<u>Optimizer to be Used</u>
1	<i>Fletcher-Reeves algorithm for unconstrained minimization.</i>
2	<i>Davidon-Fletcher-Powell (DFP) variable metric method for unconstrained minimization.</i>
3	<i>Broydon-Fletcher-Goldfarb-Shanno (BFGS) variable metric method for unconstrained minimization.</i>
4	<i>Method of Feasible Directions for constrained minimization.</i>
5	<i>Modified Method of Feasible Directions for constrained minimization.</i>

### *One-Dimensional Search*

Table V lists the one-dimensional search options available for unconstrained and constrained optimization problems. The parameter ISERCH selects the search algorithm to be used.

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*Table V. One-Dimensional Search Options*

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<u>ISERCH</u>	<u>One-Dimensional Search Option</u>
1	<i>Find the minimum of an unconstrained function using the Golden Section method.</i>
2	<i>Find the minimum of an unconstrained function using the Golden Section method followed by polynomial interpolation.</i>
3	<i>Find the minimum of an unconstrained function by first finding bounds and then using polynomial interpolation.</i>
4	<i>Find the minimum of an unconstrained function by polynomial interpolation/extrapolation without first finding bounds on the solution.</i>
5	<i>Find the minimum of a constrained function using the Golden Section method.</i>
6	<i>Find the minimum of a constrained function using the Golden Section method followed by polynomial interpolation.</i>
7	<i>Find the minimum of a constrained function by first finding bounds and then using polynomial interpolation.</i>
8	<i>Find the minimum of a constrained function by polynomial interpolation/extrapolation without first finding bounds on the solution.</i>

---

### *Allowable Combinations of Algorithms*

Not all combinations of strategy, optimizer, and one-dimensional search are meaningful. For example, it is not meaningful to use a constrained one-dimensional search when minimizing unconstrained functions. Table VI identifies those combinations of algorithms which are meaningful in the T/STAEBL program. In this table, an X is used to denote an acceptable combination of strategy, optimizer, and one-dimensional search, while an O indicates an unacceptable choice of algorithm. To use the table, start by selecting a strategy. Read across to determine the admissible optimizers for that strategy. Then, read down to determine the acceptable one-dimensional search procedures. From the table, it is clear that a large number of possible combinations of algorithms are available.

*Table VI. Program Options*

<u>Strategy</u>	<u>Optimizer</u>				
	<i>1</i>	<i>2</i>	<i>3</i>	<i>4</i>	<i>5</i>
<i>0</i>	<i>X</i>	<i>X</i>	<i>X</i>	<i>X</i>	<i>X</i>
<i>1</i>	<i>X</i>	<i>X</i>	<i>X</i>	<i>O</i>	<i>O</i>
<i>2</i>	<i>X</i>	<i>X</i>	<i>X</i>	<i>O</i>	<i>O</i>
<i>3</i>	<i>X</i>	<i>X</i>	<i>X</i>	<i>O</i>	<i>O</i>
<i>4</i>	<i>X</i>	<i>X</i>	<i>X</i>	<i>O</i>	<i>O</i>
<i>5</i>	<i>X</i>	<i>X</i>	<i>X</i>	<i>O</i>	<i>O</i>
<i>6</i>	<i>O</i>	<i>O</i>	<i>O</i>	<i>X</i>	<i>X</i>
<i>7</i>	<i>O</i>	<i>O</i>	<i>O</i>	<i>X</i>	<i>X</i>
<i>8</i>	<i>O</i>	<i>O</i>	<i>O</i>	<i>X</i>	<i>X</i>
<i>9</i>	<i>O</i>	<i>O</i>	<i>O</i>	<i>X</i>	<i>X</i>
<u>One-Dimensional Search</u>					
<i>1</i>	<i>X</i>	<i>X</i>	<i>X</i>	<i>O</i>	<i>O</i>
<i>2</i>	<i>X</i>	<i>X</i>	<i>X</i>	<i>O</i>	<i>O</i>
<i>3</i>	<i>X</i>	<i>X</i>	<i>X</i>	<i>O</i>	<i>O</i>
<i>4</i>	<i>X</i>	<i>X</i>	<i>X</i>	<i>O</i>	<i>O</i>
<i>5</i>	<i>O</i>	<i>O</i>	<i>O</i>	<i>X</i>	<i>X</i>
<i>6</i>	<i>O</i>	<i>O</i>	<i>O</i>	<i>X</i>	<i>X</i>
<i>7</i>	<i>O</i>	<i>O</i>	<i>O</i>	<i>X</i>	<i>X</i>
<i>8</i>	<i>O</i>	<i>O</i>	<i>O</i>	<i>X</i>	<i>X</i>

### *Optimizer Output Control*

The ADS optimizer output is controlled in T/STAEBL by the IOU parameter. This parameter is a four-digit control, IOU=IJKL where I, J, K, and L have the following definitions:

I: ADS system print control.

- 0 - No print.
- 1 - Print initial and final information.
- 2 - Same as 1 plus parameter values and storage needs.
- 3 - Same as 2 plus scaling information calculated by ADS.

J: Strategy print control.

- 0 - No print.
- 1 - Print initial and final optimization information.
- 2 - Same as 1 plus OBJ and X at each iteration.
- 3 - Same as 2 plus G at each iteration.
- 4 - Same as 3 plus intermediate information.
- 5 - Same as 4 plus gradients of constraints.

K: Optimizer print control.

- 0 - No print.
- 1 - Print initial and final optimization information.
- 2 - Same as 1 plus OBJ and X at each iteration.
- 3 - Same as 2 plus constraints at each iteration.
- 4 - Same as 3 plus intermediate optimization and one-dimensional search information.
- 5 - Same as 4 plus gradients of constraints.

L: One-dimensional search print control.

- 0 - No print.
- 1 - One-dimensional search debug information.
- 2 - More of the same.

Example: IOU = 3210 corresponds to I=3, J=2, K=1, and L=0.

#### **2.1.1 Using ADS in the Restart Mode**

Due to the shell execution mode of T/STAEBL, the ADS optimizer is being used in a different mode than was employed in Aero/STAEBL (Reference 2). Instead of being called repeatedly in a single program execution, ADS is now being executed from a cold start each time it is referenced. While ADS is purported to support this mode of analysis, we have located several errors in the Version 2.0 that we were using. For this reason, the ADS version in T/STAEBL is slightly changed over that employed in Aero/STAEBL, and is different from the delivered Version 2.0. Do not change to a new optimizer before validating its cold restart capability!

Since the optimizer is being called as a module of the T/STAEBL system, it must get the optimization history from a data file, for it to make its design move and gradient decisions. These data, as well as the outputs from ADS, are carried in the ADSARG file (Block 500).

## 2.2 Design Curves

In order to maintain computational effectiveness in T/STAEBL, the number of design variables required to produce meaningful design improvements has been minimized by providing for the perturbation of the section by section blade design through design curves, which allow changing design values at many sections by changing a small number of design variables. Any design parameter that may have values at several radial sections is splined to fit a design curve. By allowing variations on that design curve, T/STAEBL gives maximum design flexibility with a minimum of design variables, saving both analyst and computer time.

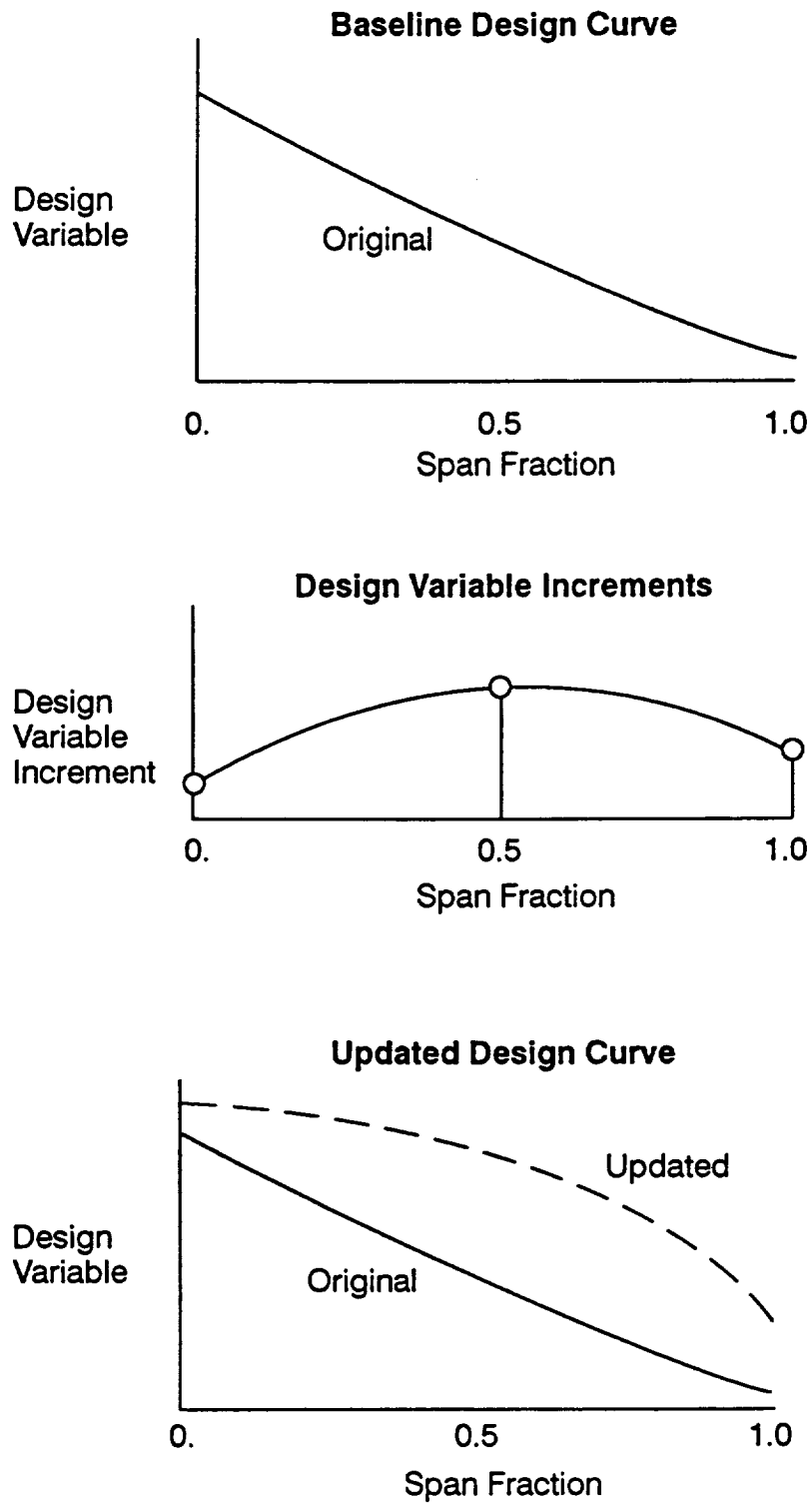
By allowing the analyst to select the number of design variables he/she wants to use in the radial direction for any particular design curve, T/STAEBL permits the analyst to tailor the flexibility of the design optimization, while maintaining effective run times. Present experience has shown design tailoring success with up to 40 design variables used.

### *Design Data Curves*

In T/STAEBL, except for five discrete quantities such as the coating thickness, all design data is stored in tabular form as splines of design curves. The design curves are defined in the program as data values with a corresponding abscissa, the section radius. The entire internal cooling scheme description is stored in these design tables. Using quintic spline algorithms, design curve references are available, so that any curve may be referenced at any arbitrary required radial location.

As the design optimization process commences, it is necessary for T/STAEBL to update the design curves to reflect the present analysis geometry. Thus, two sets of design curves are maintained – an original set of curves, and a current set. The baseline design curves are updated via design curve increments. A detailed definition of the curve increments is determined via a spline fit of available design variables. Thus, any curve may be updated by having one or more design variables assigned to it. The updated curve is splined, then added to the baseline curve, thus creating the current design curve, from which the analysis geometry is derived, as shown in Figure 3.

By using the curve incrementing procedure, several advantages are obtained. First, it is always possible to reproduce a baseline design. If the design variables are the curve values themselves, rather than increments, it is difficult to regenerate a baseline geometry without an inordinate number of design variables. By splining increments of baseline curves, a design variable set of zeroes always reproduces the original design. Secondly, the process allows for reducing the optimizer design variable requirements by providing for dependent variables and for constant terms. A dependent variable assignment allows for a curve to be incremented at several abscissa locations even though it may have only one design variable attributed to it. Dependent variables are incremented in user prescribed ratios to the actual design variables, and are unknown to the optimizing algorithm. The provision of a constant parameter allows a curve location to be held to a constant value via a prescribed zero increment.



**Figure 3** *Splined Design Variables From Curve of Design Increments Which Update the Baseline Design*

## *User–Friendly Features*

To simplify usage of the STAEBL program and reduce the chances for errors in creating optimization cases, many user–friendly enhancements have been added to the STAEBL system. For the optimization control, input cards are identified by mnemonic titles, and free format inputs are utilized, thus streamlining the data file creation process. Design definition parameters are input as sets of data on CURVE cards, which reference an ABSCISSA card which provides section geometry location. Independent design variables are identified on VARIABLE cards, which provide curve and abscissa value reference for a design variation location. Design variable upper and lower change limits, and initial values for the design variable are also provided. This capability for an initial nonzero value of the design variable provides the program with a restart capability. Associated with the design variables, and providing additional curve perturbation information, are the DEPENDent variables and the CONSTANT terms, which allow curve values at specified locations to be kept constant or to be varied in fixed proportion to variations at design variable locations. These added curve options provide increased program flexibility, and more detailed design curve description, at no additional analysis cost.

### **2.3 Cooled Airfoil Analysis**

The purpose of this section is to describe details of the cooled blade thermal and flow analysis systems which determine the performance characteristics of each candidate design proposed by the T/STAEBL optimization system.

#### **2.3.1 Overall Process**

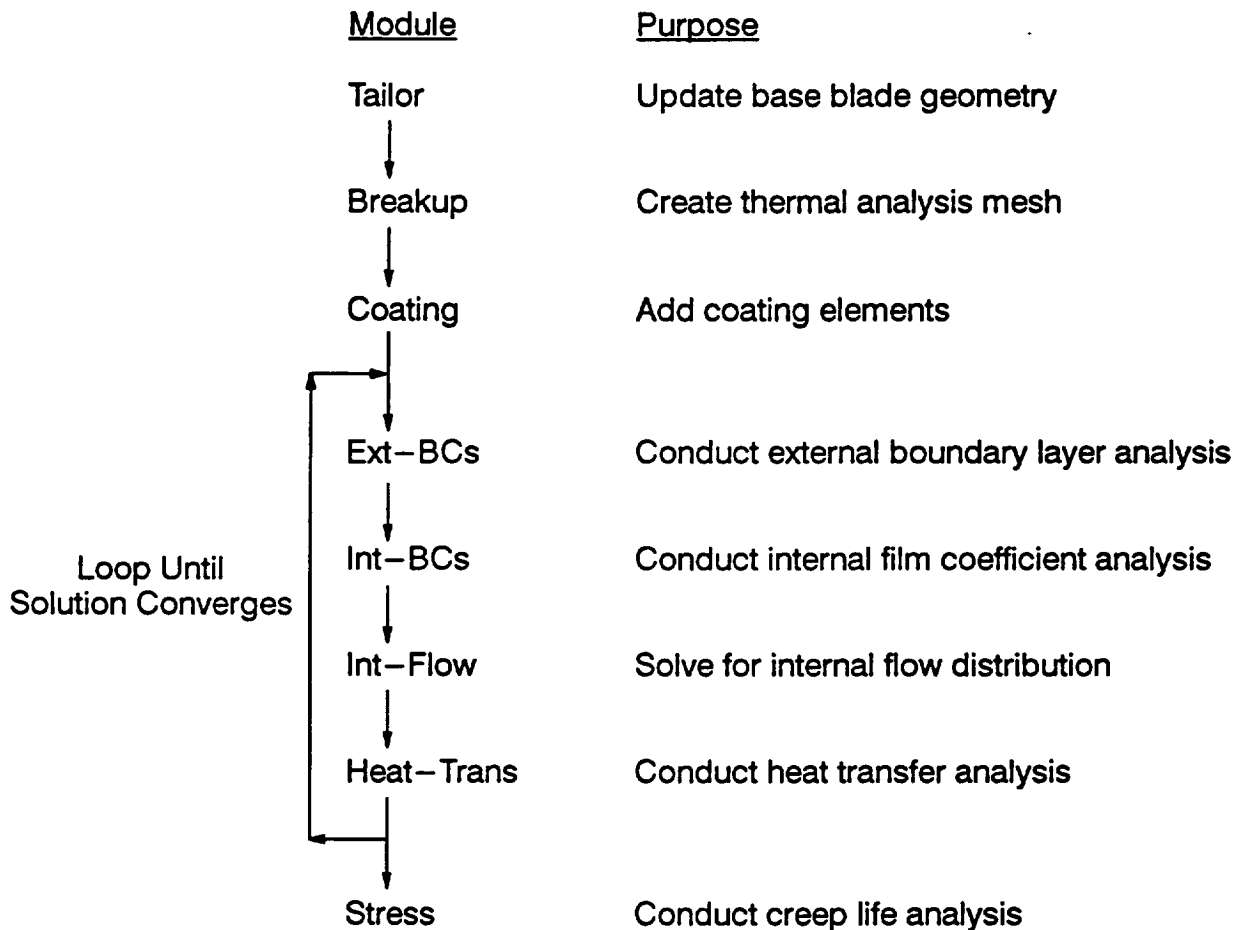
Within the analysis process for each candidate design, many analysis modules are involved in the cooled blade evaluation process. These modules all execute separately, with the analysis flow controlled by the execution shell. Modules communicate with each other through the data block system. Figure 4 details the cooled blade thermal analysis flow.

Program V541I serves as an analysis initialization step, transferring several required base (original design) design files from the storage library to a temporary analysis area.

Program V541A is an interpreter of the design change requests passed down for analysis by the optimizer. This module, also called the Tailor module, modifies the original blade geometry to create a modified geometry for design evaluation. Due to the rather specific nature of the geometry alterations available within T/STAEBL, Tailor code modification will be required for application of this optimization algorithm to geometries that are radically different from the triple pass cooled airfoil Energy Efficient Engine designs employed for this effort. This module creates updated geometry description blocks to reflect the altered blade design, updating blocks 1, 23, 37, 104, 501, 521, and 513.

The Breakup program, V548, is a processor that uses coarse breakup blocks, identified in Block 512, to create a refined mesh of elements for heat conduction analysis. The definitions for these thermal elements are stored in blocks 90, 91, and 92. These elements, in addition to conduction analysis, are used as interface processors which remap results from a processor to the associated boundary condition block.

The V547 Coating analysis is a module that adds a layer of coating to the airfoil by adding a face set of elements to the outer surface of the primary airfoil. These elements are given a thickness equal to that of the coating, and are usually meshed to fit the existing refined elements of the primary airfoil.



**Figure 4**     *Cooled Airfoil Analysis Subsystem Flow*

The V541A, V548, and V547 analysis programs all fall within an iteration loop, to generate geometries and breakups for each of the five airfoil cross-sections that will be analyzed. After all section geometries have been generated, an exit from the thermal analysis system is provided. This exit is utilized on the very first analysis pass, when the shell wants to generate an initial geometry, but is not yet ready to perform a design analysis. After this initialization, all passes through the thermal analysis system will include both the geometry and analysis modules.

The first analysis module, V541B, updates the network model of the airfoil geometry, based on the current values of the design parameters, and the results of the airfoil remodelling that has been performed by the previous modules.

The V541C module calculates the centrifugal pull forces associated with the updated airfoil geometry.

At this point, the T/STAEBL thermal analysis system is ready to begin a complete, steady-state analysis of the updated hollow airfoil geometry. This analysis process is an iterative one because the boundary conditions for one part of the analysis can change as the results of other modules of the analysis loop are received. To allow all boundary conditions to reach a converged state, a simple iteration procedure is employed. Starting with the converged boundary conditions of the previous

analysis pass, this thermal analysis iteration loop is performed three times. Experience has shown that three passes through this analysis loop provide adequate boundary condition convergence for the T/STAEBL optimization procedure.

Within this iterative analysis loop, the first module employed is the V544 Network analysis. This processor determines the flow distribution through an airfoil, using network geometry and one-dimensional correlations for internal geometry features. Outputs include temperatures and heat transfer coefficients from the airfoil interior, and also the mass flow of the coolant. Results apply to all sections of the airfoil.

At this point, a loop is entered and three analysis modules, along with three boundary condition update processors, are executed for the interior three cross-sections of the airfoil. The V542 Boundary Layer analysis performs a numerical solution of the boundary layer equations to determine external heat transfer coefficients.

The V543 Film analysis uses correlations associated with film cooling to identify the differences between uncooled external heat transfer coefficients and those that exist downstream of film holes.

With both the external and internal heat transfer boundary conditions determined, the Conduction Analysis module (V545) is executed to solve for the heat transfer that occurs inside the metal portions of the airfoil. This program is a finite difference solution to the heat conduction equations.

After the heat transfer analyses have been performed, three modules are executed to update the boundary conditions associated with these analyses. Two more passes are made through this iterative solution to ensure convergence of the thermal analyses.

After the airfoil thermal condition has been determined, a life prediction analysis is called. For blades, this V546 analysis calculates the stresses in each of the airfoil elements, assuming that the elements are free to slip between each other. As some of the elements move into a yielded condition, where yield at the element temperature is obtained from the Block 12 material properties file, the life prediction module accumulates the yield deflection as a portion of the component life.

For vanes, the life prediction is performed by the V546V module, which uses an empirically based calculation to calculate the oxidation life of the part.

### **2.3.2 Network Processor (V544)**

This analysis module uses a network model, along with one-dimensional flow correlations, to model the interior of the airfoil. Figure 5 illustrates the model for the Energy Efficient Engine first blade. The network consists of nodes, placed where flows join or separate, and paths which connect these nodes. As the air distributes throughout the network, pressure loss and temperature increase are accumulated, so that the state of the air entering each passage is determined.

Fundamental to this network processor are the correlations which are used to model the interior passages. For the type of analyses included in the T/STAEBL system, both friction and heat transfer correlations are an important part of the network calculation.

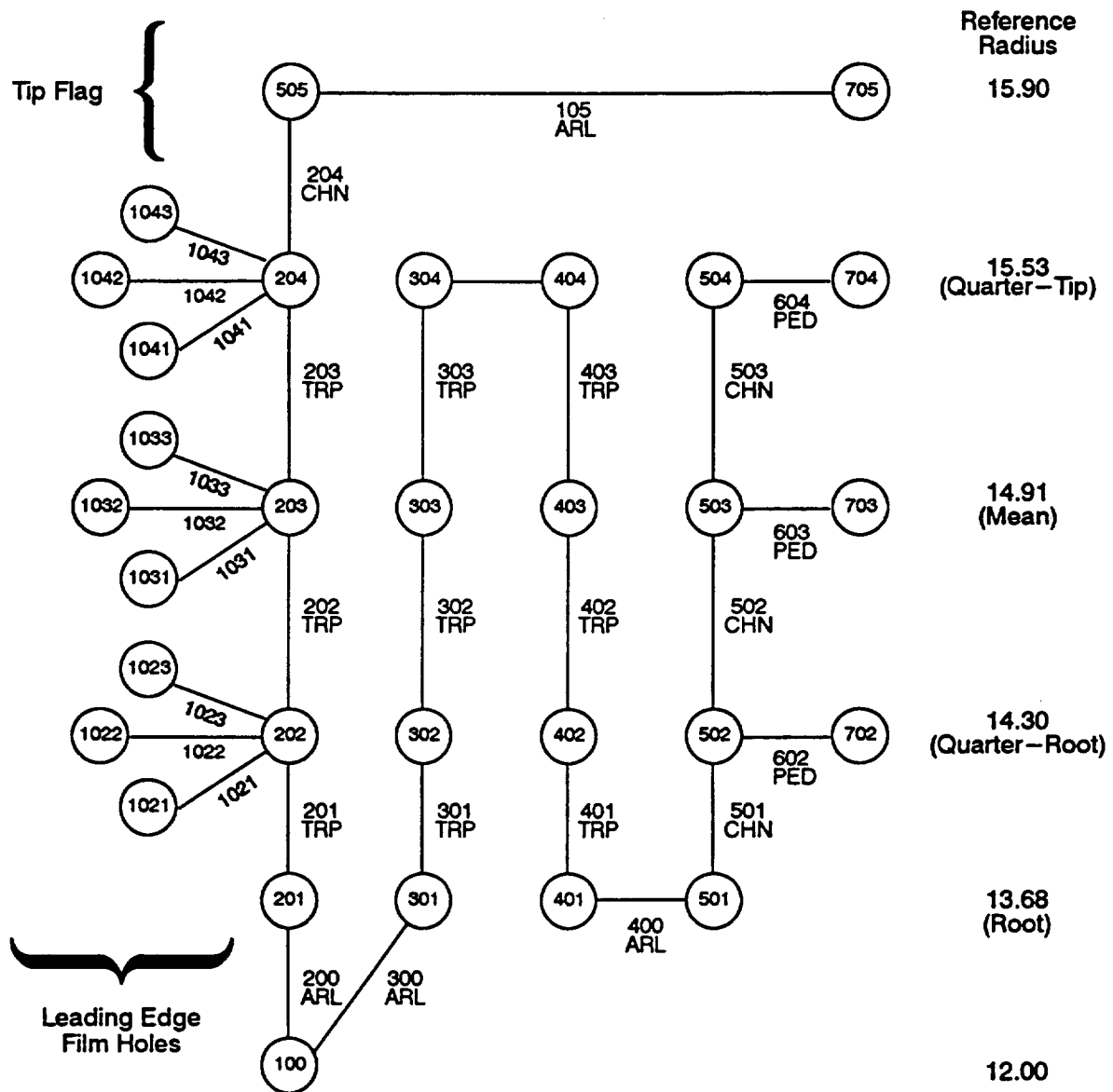


Figure 5 Network Node-Path Map

### Smooth Wall Correlations

Smooth walls are modelled using classical correlations for the flow inside smooth tubes. The following flow correlations, obtained from Reference 8, are used. For friction,

$$\frac{\Delta P}{Q} = \frac{fL}{D} \quad \text{where } f = 0.08 * Re^{-0.25}$$

For heat transfer,

$$Nu = 0.023 * Pr^{0.4} * Re^{0.8}$$

### Trip Strip Correlations

Trip strips increase both the friction and the heat transfer within a passage by making the flow more turbulent. The correlation used for T/STAEBL (Reference 9) is a model developed by Han, Park, and Ibrahim in 1986. This model includes variations as trip strip size and spacing vary, and also includes the effect of trip strip angle. Correlational values are given for both smooth wall and rough wall friction and heat transfer values.

In most airfoil passages with trip strips, a portion of the walls is smooth and a portion is roughened with the trip strips. The correlation used in T/STAEBL combines the smooth wall and rough wall values of friction and heat transfer coefficient based on the relative portion of each wall type.

For friction:

$$FS = 0.079 * REY ** (-0.25)$$

For smooth wall friction.

$$A = \text{ABS}(90.0 - \text{ANGL})/90.0$$

A is an angle parameter.  
(Normal TS = 90.0 Degrees)

$$Z1 = 12.31 - 27.07 * A + 17.86 * A ** 2$$

$$Z2 = (0.1 * PE) ** 0.35 * (1.0/E) ** 0.35$$

$$RFMT = Z1 + Z2$$

RFMT is a parameter of the correlation used to get the rough wall friction.  
PE is pitch/height ratio.  
E is rough/smooth perimeter ratio.

$$Z3 = 2.0 * HTH * 2. / (1.0 + E)$$

$$Z4 = 1.0 + \text{LOG}(Z3)$$

$$FR = 2.0 * (1.0 / (RFMT - 2.5 * Z4)) ** 2$$

FR is the rough wall friction.  
HTH is the height/hydraulic diameter.

The friction factor along the passage is then a combination of the smooth wall friction factors,

$$F = (FR + E * FS) / (1.0 + E)$$

A similar approach is taken in determining the heat transfer correlations:

$$EPLUS = EH * REY * \text{SQRT}(0.5 * FR)$$

$$RFHT = 2.24 * (1/E) ** 0.1 * (EPLUS) ** 0.35$$

EPLUS and RFHT are correlation parameters.  
EH is the trip height/passage height.

$$STS = 0.023 * REY ** (-0.2) * PR ** (-0.6)$$

STS is the smooth wall heat transfer, in the form of the Stanton Number.

$$Z1 = 1.0 / (1.0 + \text{SQRT}(0.5 * FR) * (RFHT - RFMT))$$

$$STR = 0.5 * FR * Z1$$

STR is the rough wall heat transfer, in the form of the Stanton Number.

$$ST = (STR + E * STS) / (1.0 + E)$$

ST is the passage heat transfer, in the form of the Stanton Number.

### *Pedestal Correlations*

Pedestal friction is determined based on a correlation by Metzger as reported in a survey paper by Armstrong and Winstanley, Reference 10.

$$F = 0.317 * REYD ** (-0.132)$$

REYD is the Reynolds number, based on pedestal diameter.

Heat transfer is in terms of the Nusselt Number,

$$Nu = 0.135 * REYD ** 0.69 * (XC/DC) ** (-0.34)$$

where XC is the spacing, and DC is the pedestal diameter.

### **2.3.3 External Boundary Layer Analysis (V542)**

The T/STAEBL external boundary layer analysis employs the STAN-5 computer program for the solution of the boundary layer equations. The program (Reference 11) is an outgrowth of the original procedure developed by Pantankar and Spalding at Imperial College, London. The program solves the momentum equation plus any number of diffusion equations.

The STAN-5 program has been modified for T/STAEBL, so that users are not required to input starting boundary layer profile data. Instead, details of the leading edge are used to generate a classical starting boundary layer.

### **2.3.4 Film Cooling Analysis (V543)**

Film cooling correlations are typically curves that give the cooling effectiveness versus a parameter ( $X / MS$ ).

Cooling effectiveness is a measure of how well the cooling process is performing:

$$\text{Effectiveness} = \frac{T_{\text{wall}} - T_{\text{gas}}}{T_{\text{coolant}} - T_{\text{gas}}}$$

An effectiveness near 1.0 means that the wall temperature is nearly equal to the coolant temperature. As wall temperature increases toward the gas temperature, the cooling effectiveness drops, falling somewhere in a range between 1.0 and 0.0.

Effectiveness is usually plotted against ( $X / MS$ ), where X is the distance downstream from the film cooling holes. This X distance is normalized by dividing by the equivalent slot width, S. For a two-dimensional slot, S is just the slot width. For a row of holes, S is determined by converting the hole area into an equivalent slot width. Thus, ( $X / S$ ) represents a non-dimensional distance downstream from the coolant flow source.

In the (X / MS) coordinate, M is the blowing parameter, and represents the ratio of fluid momentum of the jet leaving the cooling holes and the fluid momentum of the main stream flow. Very high values of M usually mean that the jet is blowing directly into the main stream air, and is not attaching to the surface to be cooled.

The data used for the T/STAEBL program were obtained from Jabbari and Goldstein (Reference 12), on cooling downstream of film holes.

### 2.3.5 Conduction Analysis (V545)

The T/STAEBL conduction analysis is a finite difference solution of the heat transfer equations. The analysis uses the two-dimensional element breakup generated by the V548 and V547 modules, and also on the material properties stored in data Block 12. Boundary conditions for this analysis are obtained from the V542 and V543 modules for external conditions, and V544 for internal conditions.

### 2.3.6 Stress and Creep Analysis (V546)

The V546 Stress and Creep Analysis module calculates the out-of-plane (radial) stress distributions for turbine airfoils. An overriding physical assumption is that plane cross-sections remain plane after deformation. For setting up solution equations, the program uses a lumped parameter technique in which loads, temperatures, and material properties are lumped together at the approximate centroids of the finite elements. The nonlinear solution is then obtained through the use of a generalized Newton-Raphson iteration procedure.

Creep is included in the analysis as a change in creep strain over a time increment sufficiently small so that the stress can be considered constant over the interval. At the end of each time increment, the creep strain is added to previously accumulated strains. The program continues until a user-specified life fraction, defined as life used divided by life available based on stress rupture, is reached.

### 2.3.7 Oxidation Life (V546V)

The analysis processes for blades and vanes are very similar, except for the life prediction model that is used. Blades are typically creep life limited. Vanes, however, experience much smaller stresses, and no centrifugal loads. Lives for vanes are usually limited by oxidation considerations.

The V546V module uses an empirical formulation of vane life which is influenced by the highest temperature on the surface of the airfoil, and the thickness of the coating.

## 2.4 Objective Function

The T/STAEBL cooled airfoil optimization analysis seeks to minimize a user-defined objective function that consists of a summation of the products of weighting factors and associated performance parameters. The intent is to allow the generation of a general cost of operation function for the aircraft so that T/STAEBL can intelligently trade airfoil weight, cooling flow requirements, aerodynamic losses, and blade durability, to achieve an airfoil design that leads to a minimum cost aircraft. The T/STAEBL objective function may be expressed as follows:

$$OBJ = \sum_{i=1}^8 W_i * Pparam_i$$

The weighting factors,  $W_i$ , are determined from aircraft cost of operation cost studies. These factors are input by the user on the OBJECTIV data card.

The performance parameters, Pparam<sub>i</sub>, are evaluated by the appropriate T/STAEBL analysis modules. These parameters are:

1. WEIGHT      –      Single airfoil weight, lb
2. RSP/A        –      Root section airfoil net radial stress, psi
3. CFLRATE     –      Coolant flow rate, %Wac
4. AVPRLOSS    –      Average profile loss, pt/pt
5. AVFMLOSS    –      Average film mixing loss, pt/pt
6. MAXTEMP     –      Maximum airfoil metal temperature, °F
7. AVBLTEMP    –      Average airfoil metal temperature, °F
8. PL1FEUSE    –      Percent of life used in 10 hours of service.

## **2.5 Cooled Blade Structural Analysis**

### **2.5.1 Airfoil Finite Element Mesh Generation**

Within the T/STAEBL system is the capability to change the thicknesses of walls and ribs. These changes must be reflected in any finite element model of the blade to assure a proper coupling with the changes being made to the design.

This interaction of structural and thermal analyses has been effectively included in T/STAEBL by interfacing the finite element mesh generator with the TAILOR cooled blade design update module. The TAILOR module outputs the airfoil updated geometry to several “current” data blocks. The data block used by the finite element mesh generator is Block 91, which contains information relevant to the thermal breakup as well as the structural breakup.

In its entirety, Block 91 contains coordinates of the thermal analysis element centers for elements on the airfoil interior, and all free surfaces. For the T/STAEBL structural finite element mesh generator, only the interior element centroids are utilized. To determine how many elements are employed on the interior of the airfoil thermal mesh, the user must run T/STAEBL for a single, partial analysis pass, as discussed in the T/STAEBL User’s Manual (Reference 1). Tailor will create Block 517, which contains just a single number – the uncooled (interior) element count.

The user must then plot a representative section, as shown on Figure 6, which includes the centroidal point number. The Figure 6 plot was completed in the Lotus 1–2–3 spreadsheet program. Plotting accuracy is not essential, but the user must be able to discern the element number, which is key to the connectivity of the finite element mesh.

At this point the user is ready to construct the representative cross–section finite element mesh, by connecting the appropriate dots on the plot, as shown in Figure 7. CAUTION – do not use an excessive number of lines on a cross–section, for you will end up with high run times, and perhaps exceed the capability of the T/STAEBL finite element analysis. Once the mesh has been defined, the user can now select node numbers, alternating sides, as on Figure 7, to minimize the band width. A cross–reference list of thermal breakup node number to finite element node number is thus created, becoming Block 502.

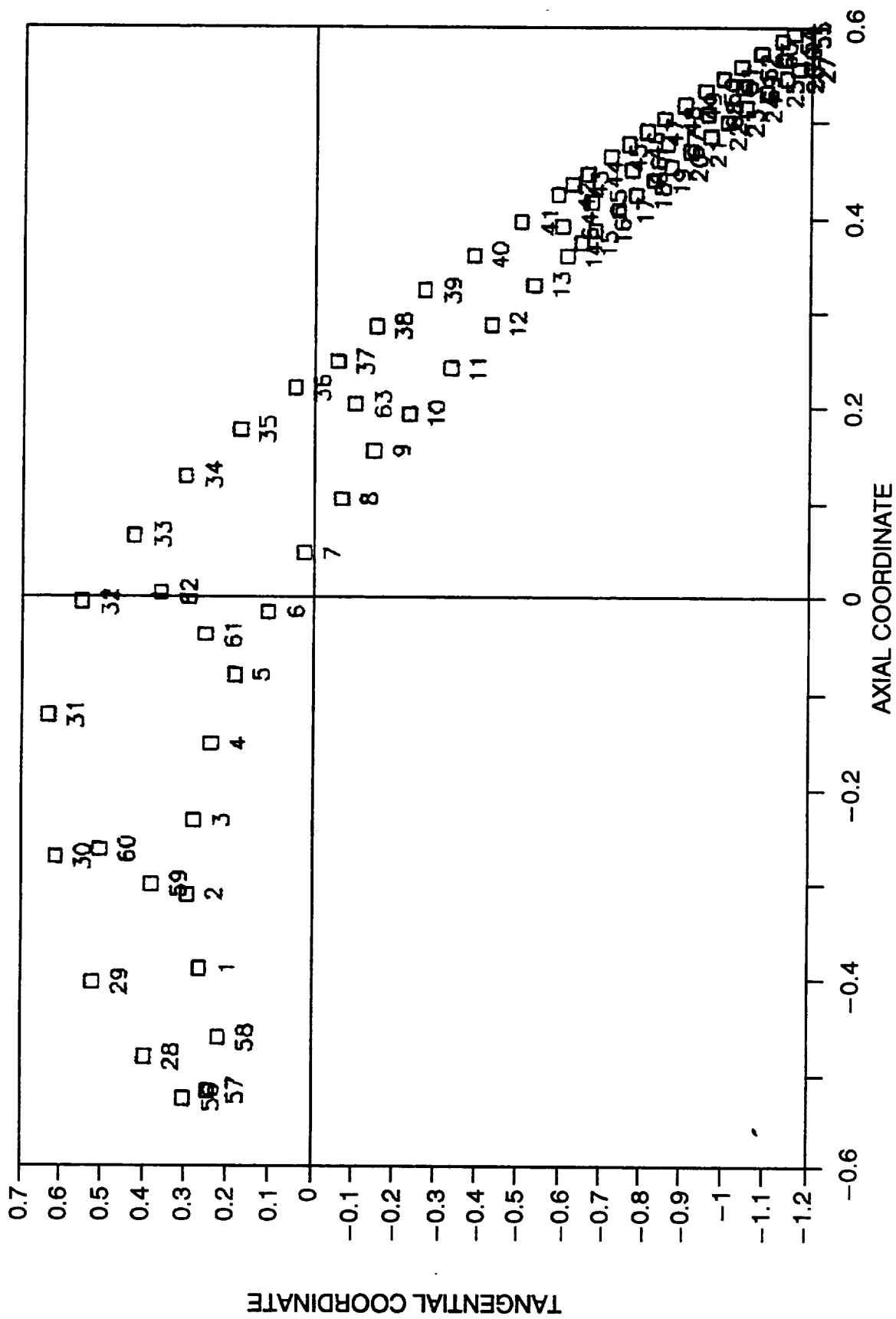


Figure 6 Thermal Analysis Element Centers

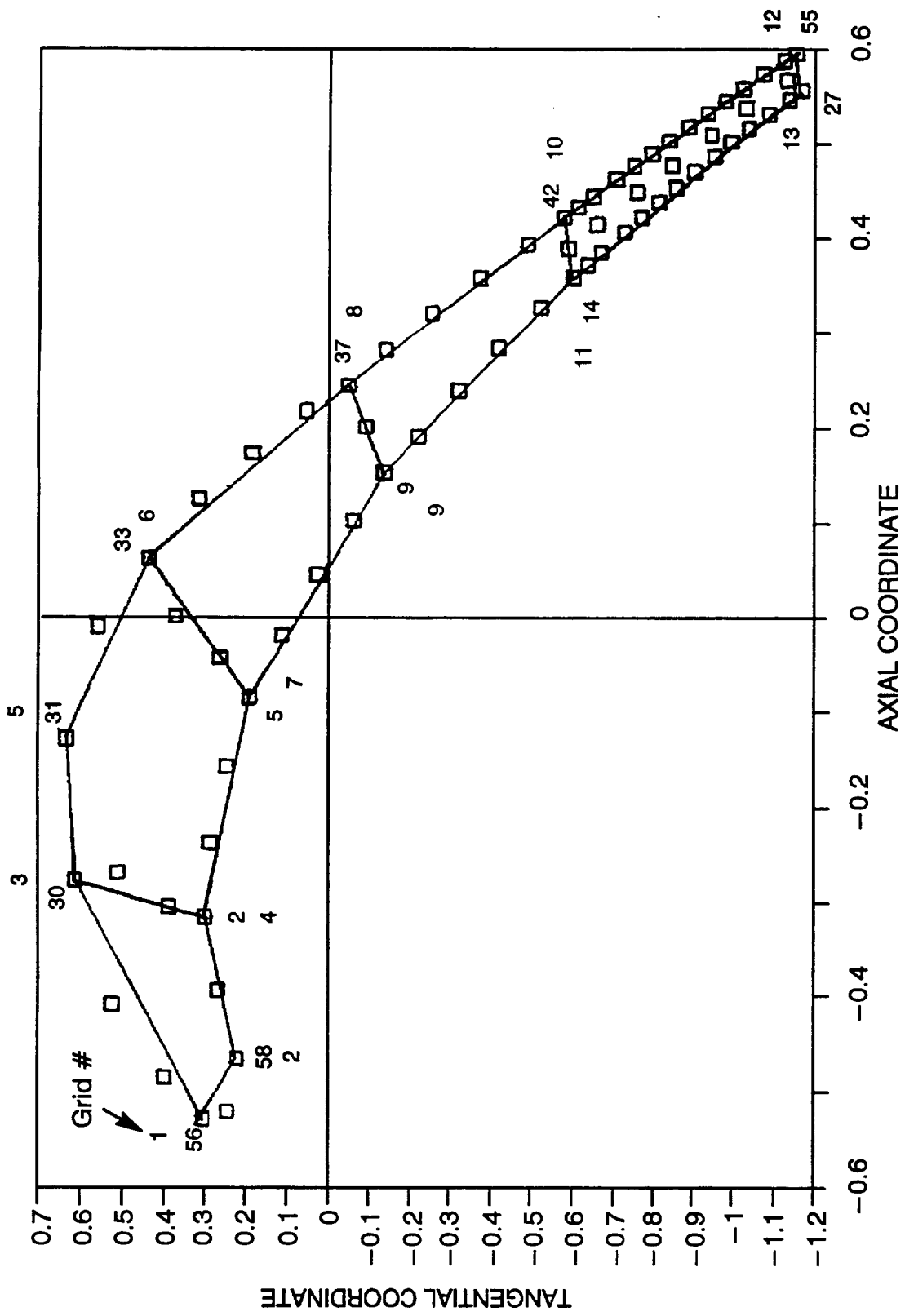


Figure 7 Cross Section Finite Element Mesh

A second list in Block 502 tells the mesh generator how to connect the selected cross-section nodal points to construct the airfoil mesh. Along with the description of the edge of the element, an identifying attribute is ascribed to the element. This attribute cross-references to a component thickness list, which is also generated by the TAILOR module, and stored in Block 509. Thus, when the finite element mesh is created, both correct nodal locations and element thicknesses will be generated for the candidate design.

The meshing module now has sufficient information to build the proper finite element mesh for any blade generated by the TAILOR module. The T/STAEBL program will take the information in Block 502, and translate it to other sections, creating the blade structural mesh, as shown on Figure 8. Using this procedure, the mesh of the entire airfoil is created.

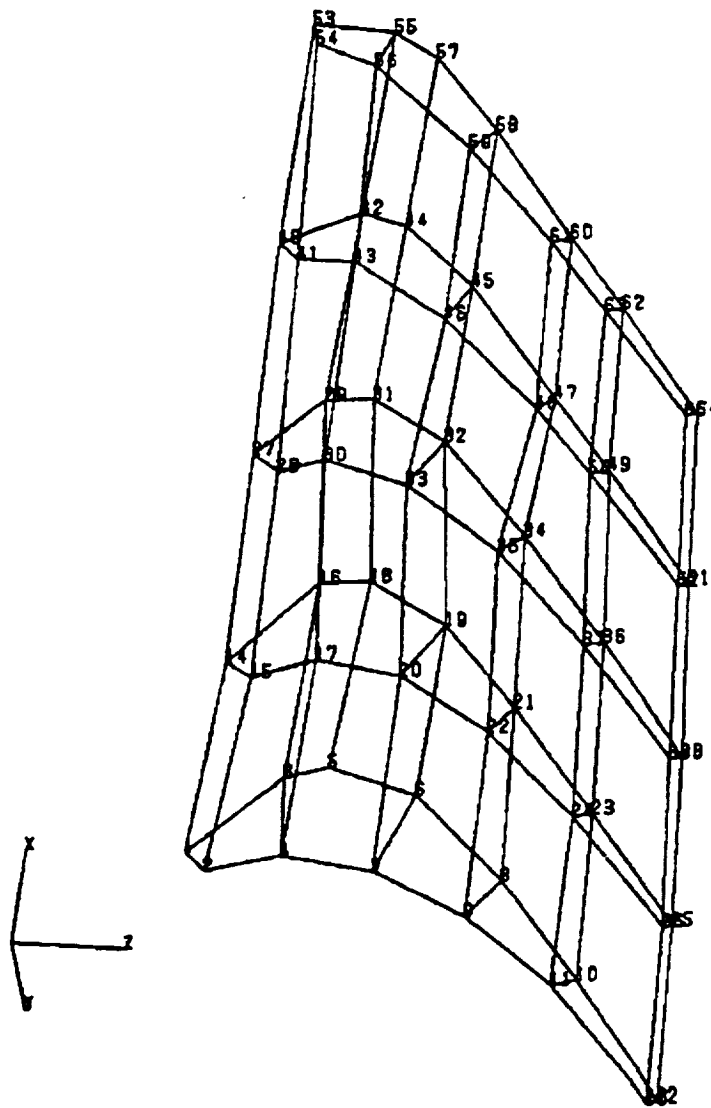


Figure 8 Airfoil Finite Element Mesh

### 2.5.2 Airfoil Neck Model

To model the airfoil attachment and extended neck regions, a beam representation has been found sufficiently accurate for frequency determinations. In T/STAEBL, two options are available. If no NECKGEOM card is included in Block 503 of the input data, the airfoil will be fully restrained at its root. Attachment and neck flexibility may be included by using the NECKGEOM option.

When a NECKGEOM card is included, T/STAEBL will model the attachment to airfoil root section using a beam finite element model. The user inputs the cross-sectional (assumed constant with radius) area, bending moments of area, and torsional stiffness constant. Also included is an orientation, or broach, angle. Using a finite element much like the NASTRAN CBAR, a model of the extended neck section is generated, and utilized by the finite element module.

At its inner radius, the model of the airfoil neck is currently cantilevered. Attachment springrates are available in the T/STAEBL finite element code, but have not had a significant effect on natural frequency for the blades optimized to date. At the neck to airfoil intersection, where the platform normally sits, the beam neck model is attached to the plate model of the airfoil root using rigid body elements to generate the proper kinematic displacement relationships. These constraints are generated automatically to all root section GRIDS within T/STAEBL, using the cross-section breakup information of Block 502.

### 2.5.3 Model Performance

The finite element mesh of Figure 8 was used for analysis of the Energy Efficient Engine first-stage turbine blade. In total, it contains 68 grids points and 83 quadrilateral plate elements. The stiffness matrix has a semi-bandwidth of 102. To run the analysis, the finite element code must have work storage of 1 megabyte available. Execution of all the T/STAEBL modules took 58 seconds per full function call on an IBM-3090.

The T/STAEBL finite element turbine blade model compares quite well with much more detailed NASTRAN analysis. Table VII shows the frequency comparisons between the detailed NASTRAN model and the approximate T/STAEBL model. The detailed results were generated in the design phase for the Energy Efficient Engine.

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*Table VII. Energy Efficient Engine High Pressure Turbine Frequency Analysis Comparisons*

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<u>Mode</u>	<u>Detailed NASTRAN Model (cps)</u>	<u>T/STAEBL (cps)</u>
1	1788	1800
2	2616	2617
3	3178	3287

---

## **2.6 Materials Data Base**

As an aid to reducing the complexity of the T/STAEBL system inputs, a materials data base has been created. This materials data base takes properties input as tables, as coefficients of a polynomial approximation, or as spline coefficients, and creates the Block 12 materials data file required by the T/STAEBL system.

The materials data base is stored on disk, so that the user may call up data for a given material. The material property may be interactively updated, and/or viewed graphically by the user. Provisions have been made to edit materials currently in the system, or to add additional materials to the data base.

Details for use of the materials data base are included in Appendix A of Reference 1.

### 3. T/STAEBL VALIDATION

A comprehensive test case has been conducted to demonstrate the cooled airfoil optimization capabilities of the T/STAEBL system. The test case derives from the Energy Efficient Engine (EEE) design, which was designed under NASA Contract NAS3-20646, and consists of a full Thermo-Structural optimization of the first turbine blade, which is a cooled, triple pass airfoil. This blade configuration includes trip strips, cooling holes, pedestals, and every other complication common to modern, cooled airfoils.

#### 3.1 EEE First Turbine Blade Optimization

The inputs for the turbine blade optimization test case include all those data blocks required for running the T/STAEBL system, as detailed in the T/STAEBL User's Manual (Reference 1).

The first turbine blade finite element structural model was built as detailed in Section 2.5, and contained 68 nodal points, serving as vertices for 83 quadrilateral shell elements. Each of the cavity walls and each of the ribs are modelled. At the trailing edge of the airfoil, pedestal groups are modelled using additional quadrilateral rib elements. Five radial stations are employed for this approximate model.

##### *Design Variables*

For this cooled blade optimization, 14 design variables were employed. As will be seen, the constraints are frequency constraints. As such, the design variables utilized were ones which could have a frequency impact on the blade. Six of the design variables were assigned to the thickness of the ribs between cavities. A variable thickness was assigned to the thickness of each of the three ribs at the root and at the tip of the airfoil. The curve splining algorithm of T/STAEBL thus allows for linear thickness change variations for each rib between root and tip.

The remaining eight design variables were assigned to variations in the thickness of the wall of each side of each cavity at the tip of the blade. As such, the T/STAEBL blade optimizer had a lot of freedom for varying the structural design of the EEE first turbine blade. A complete list of the design variables employed for this optimization is:

RIB1THK1	– Rib 1, thickness at station 1 (root)
RIB1THK5	– Rib 1, thickness at station 5 (tip)
RIB2THK1	– Rib 2, thickness at station 1 (root)
RIB2THK5	– Rib 2, thickness at station 5 (tip)
RIB3THK1	– Rib 3, thickness at station 1 (root)
RIB3THK5	– Rib 3, thickness at station 5 (tip)
CV1PTHK5	– Cavity 1, pressure side thickness, tip
CV1STHK5	– Cavity 1, suction side thickness, tip
CV2PTHK5	– Cavity 2, pressure side thickness, tip
CV2STHK5	– Cavity 2, suction side thickness, tip
CV3PTHK5	– Cavity 3, pressure side thickness, tip
CV3STHK5	– Cavity 3, suction side thickness, tip
CV4PTHK5	– Cavity 4, pressure side thickness, tip
CV4STHK5	– Cavity 4, suction side thickness, tip

For a cooled blade design and optimization, nearly any reasonable structural configuration can be designed to have adequate life, simply by providing high volumes of cooling air. Thus, airfoil life is not usually considered as a design constraint, but is most often included in the objective function,

as a cost of prematurely replacing an airfoil, to be traded against the higher fuel cost associated with utilization of increased amounts of cooling air to enhance the life of the airfoil. However, if a blade is operating at a low integer multiple of its natural frequency, its life will be limited by this resonant condition, and will not be enhanced by increased cooling air flows.

Thus, in a cooled airfoil optimization, it is desirable to have frequency constraints included. Indeed, it is possible that these will be the only constraints imposed on the optimization. For the current test case, the T/STAEBL system evaluated the first two frequencies to be 1799 cps and 2620 cps for the base airfoil. For purposes of the optimization demonstration, it was decided to constrain the first frequency to be greater than 1850 cycles per second, and the second frequency to be less than 2700 cycles per second. Thus, for this demonstration, the first frequency constraint was violated by the base design. The geometry must be modified by the T/STAEBL system to achieve a feasible configuration.

To demonstrate the capabilities of the T/STAEBL system, the first test case consisted of a weight minimization of the EEE first turbine blade airfoil. As evaluated by T/STAEBL, the foil for the base blade has a weight of .208 lb.

#### *Optimization Results*

Recalling that the first frequency of the base blade is too low, one would be inclined to expect the T/STAEBL system to add mass to the root of the blade, to increase airfoil stiffness, and raise the frequency. Table VIII documents the actual design moves performed by the optimizer. Note that, while the airfoil weight increases for moves 2 and 3, the T/STAEBL system quickly finds a lighter design to be superior. It takes T/STAEBL until design 6 to reach a blade design that satisfies the frequency constraints. At this time, the foil weight is .1990 lb.

*Table VIII. Turbine Blade Optimization Design Moves*

<i>DESIGN MOVE:</i>	<i>1</i>	<i>2</i>	<i>3</i>	<i>4</i>	<i>5</i>	<i>6</i>	<i>7</i>
	<i>(BASE)</i>						
<i>OBJECTIVE FUNCTION VALUE:</i>							
<i>WEIGHT:</i>	<i>.2079</i>	<i>.2046</i>	<i>.2164</i>	<i>.2104</i>	<i>.2030</i>	<i>.1996</i>	<i>.1999</i>
<i>CONSTRAINT VALUES:</i>							
<i>FREQ 1:</i>	<i>1799</i>	<i>1833</i>	<i>1816</i>	<i>1822</i>	<i>1843</i>	<i>1872</i>	<i>1871</i>
<i>FREQ 2:</i>	<i>2620</i>	<i>2611</i>	<i>2583</i>	<i>2596</i>	<i>2607</i>	<i>2598</i>	<i>2599</i>
<i>DESIGN MOVE:</i>	<i>8</i>	<i>9</i>	<i>10</i>	<i>11</i>	<i>12</i>	<i>13</i>	<i>FINAL</i>
<i>OBJECTIVE FUNCTION VALUE:</i>							
<i>WEIGHT:</i>	<i>.1982</i>	<i>.1926</i>	<i>.1815</i>	<i>.1808</i>	<i>.1815</i>	<i>.1813</i>	<i>.1808</i>
<i>CONSTRAINT VALUES:</i>							
<i>FREQ 1:</i>	<i>1873</i>	<i>1874</i>	<i>1863</i>	<i>1863</i>	<i>1866</i>	<i>1865</i>	<i>1863</i>
<i>FREQ 2:</i>	<i>2599</i>	<i>2604</i>	<i>2637</i>	<i>2638</i>	<i>2628</i>	<i>2631</i>	<i>2638</i>

The final design selected by the system, which occurred on design move 11, has a weight (.1808 lb) that is 13 percent lighter than the weight of the base blade. Full details for the base and final designs are listed on Table IX. The details of Table IX come from the optimization report summary file, created for each run by the T/STAEBL system. This file is most useful in enabling the user to follow the progress of the run. The file includes the results of each function call. Gradient evaluations are given the flag (GE), while design moves are tagged (DM), to help the user understand the trends of the system.

*Table IX Base and Final Designs*

	<i>BASE</i>	<i>FINAL</i>
<i>OBJECTIVE WEIGHT:</i>	<i>.20786</i>	<i>.18079</i>
<i>DESIGN VARIABLES:</i>		
<i>RIB1THK1</i>	<i>0.00</i>	<i>-.01</i>
<i>RIB1THK5</i>	<i>0.00</i>	<i>-.01</i>
<i>RIB2THK1</i>	<i>0.00</i>	<i>-.01</i>
<i>RIB2THK5</i>	<i>0.00</i>	<i>-.01</i>
<i>RIB3THK1</i>	<i>0.00</i>	<i>-.01</i>
<i>RIB3THK5</i>	<i>0.00</i>	<i>-.01</i>
<i>CV1PTHK5</i>	<i>0.00</i>	<i>-.00243</i>
<i>CV1STHK5</i>	<i>0.00</i>	<i>-.01</i>
<i>CV2PTHK5</i>	<i>0.00</i>	<i>.00360</i>
<i>CV2STHK5</i>	<i>0.00</i>	<i>-.01</i>
<i>CV3PTHK5</i>	<i>0.00</i>	<i>-.00165</i>
<i>CV3STHK5</i>	<i>0.00</i>	<i>-.00929</i>
<i>CV4PTHK5</i>	<i>0.00</i>	<i>-.01</i>
<i>CV4STHK5</i>	<i>0.00</i>	<i>-.01</i>
<i>CONSTRAINTS:</i>		
<i>FREQ1</i>	<i>.02772</i>	<i>-.00718</i>
<i>FREQ2</i>	<i>-.02976</i>	<i>-.02298</i>
<i>FREQUENCIES:</i>		
<i>1ST MODE</i>	<i>1798.7</i>	<i>1863.3</i>
<i>2ND MODE</i>	<i>2619.6</i>	<i>2638.0</i>
<i>THERMAL ANALYSIS PARAMETERS:</i>		
<i>ROOT P/A STRESS</i>	<i>52311</i>	<i>51251</i>
<i>CFLRATE</i>	<i>3.661</i>	<i>3.856</i>
<i>AVPRLOSS</i>	<i>.004574</i>	<i>.004569</i>
<i>AVFMLOSS</i>	<i>.009598</i>	<i>.009598</i>
<i>MAXTEMP</i>	<i>1641</i>	<i>1649</i>
<i>AVBLTEMP</i>	<i>1210</i>	<i>1200</i>
<i>PLIFEUSE</i>	<i>.0044</i>	<i>.0173</i>

Within the summary file are listed the design parameters both in the form used by the ADS optimizer, and in a form understandable by the user. Thus, design variables are listed in both native and scaled forms. Constraints are listed in ADS form (i.e.,  $G(x) < 0$  for a satisfied constraint), but the constrained values, such as frequencies, are also listed. Additionally, the relevant thermal analysis parameters for the design are listed.

Note that for this design optimization, many of the design variables have reached their lower limit, suggesting that further weight reduction may still be possible. In only one instance, the pressure side of cavity 2, was material actually added to the blade. By removing mass from the tip of the blade, the T/STAEBL system has reached its frequency goals, while significantly reducing foil weight. To do this, cooling flow rates have increased, as well as foil temperatures. This increased temperature results in a much higher fractional life use for the airfoil, from .0044 to .0173. Should this life use become excessive, the benefits of the weight optimization could be lost.

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